Development of igneous layering during growth of pluton: The Tarçouate Laccolith (Morocco).

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Abstract

We discuss the significance of igneous layering with respect to pluton growth processes. The case study is the Tarçouate Laccolith (Morocco), whose core consists of modally layered hornblende granodiorites with high amount of monzodioritic enclaves, contrasting with peripheral, non-layered biotite granodiorites with low amount of enclaves. Rhythmic layering, with modal grading, cross-stratification and trough layering is associated with monzodioritic layers and wraps around mafic enclaves. Its steep dips ≥ 45° result from tilting that occurred above solidus conditions, as indicated by sub-vertical and synmagmatic granite, aplite and monzodiorite dykes cutting across the layering.

The systematic association of igneous layering with mafic enclaves in calc-alkaline plutons suggests that layering originates from recurrent injection of mafic magma. Viscosity calculations suggest that the physicochemical properties of magma alone cannot account for the presence of layering in the central hornblende granodiorite and its coeval absence in the peripheral biotite granodiorite of the Tarçouate Laccolith. Intermittent pulses of hot mafic magma into crystallizing granodiorite likely produced thermal perturbations able to trigger local convection, formation of mafic enclaves and development of igneous layering through protracted crystallization.

1. Introduction

The Klokken intrusion (Parsons and Becker, 1987), the Ploumanac'h massif (Barrière, 1981) and the Sierra Nevada batholith (Tobisch et al., 1997) are spectacular examples of igneous layering in syenite and granite plutons. Igneous banding (“layering” and “banding” are used according to Irvine, 1982) and schlieren have been accounted for by two main types of process, which are likely to occur concurrently in a single pluton.

One process corresponds to viscous flow related to mingling of heterogeneous magmas in dynamically evolving systems (e.g. Seaman et al., 1995). This is illustrated, for example, by mafic and silicic layered intrusions (MASLI), which involve multiple injections of mafic magma into floored, partly crystallised, silicic magma chambers (Wiebe, 1993a, Wiebe, 1993b, Wiebe, 1996, Wiebe and Collins, 1998, Collins et al., 2000 and Wiebe et al., 2002). It was further shown that mafic schlieren and layers may form through disaggregation of monzodioritic pulses interacting, at different rheological states, with silicic host-magma (Reid and Hamilton, 1987 and Gasquet et al., 1995; Wells and Wooldridge, in Pitcher, 1993).

The other process invokes movements between crystals and melt, which are linked to thermal and compositional convection and to physical melt segregation in magma chamber. This encompasses mainly gravity settling and hydrodynamic sorting related to density currents (Barrière, 1981, Parsons and Becker, 1987, Tobisch et al., 1997 and Hodson, 1998), and compaction of crystalline mush (Parsons, 1987 and Cawthorn, 1996). Additional processes may be dyking (Komar, 1972, Komar, 1976, Ramsay, 1989 and Blenkinsop and Treloar, 2001), chamber floor subsidence associated with recurrent magma replenishment (Clarke and Clarke, 1998 and Wiebe et al., 2002), and local thermal convection due to injection of mafic pulses (Weinberg et al., 2001). Recurrent magma replenishment implies low-viscosity crystal-melt suspensions, in agreement with experimental data showing that viscosities of silicic magmas cluster around $10^{4.5}$ Pa s over much of the crystallization interval, and do not change strongly as far as crystal proportion remains lower than 30–50% (Scaillet et al., 1996, Scaillet et al., 1997, Scaillet et al., 1998 and Clemens and Petford, 1999). This is consistent with current knowledge based on field, petrological and geochemical studies (e.g. Deniel et al., 1987, Ramsay, 1989, Corriveau and Leblanc, 1995, Paterson and Vernon, 1995, McNulty et al., 2000, Petford et al., 2000, Roberts et al., 2000, Saint-Blanquat et al., 2001 and Asrat et al., 2003), on relationships between mafic and silicic magma (Brémond d'Ars and Davy, 1991, Fernandez and Gasquet, 1994, Hallot et al., 1996, Wiebe and Collins, 1998 and Asrat et al., 2004), and on pluton 3D-geometry, strain consideration and thermo-mechanical arguments (Clemens and Mawer, 1992, Collins and Sawyer, 1996, Petford, 1996 and Vigneresse and Clemens, 2000).

Despite this wealth of data, the reasons whereby some plutons or part of plutons display well-developed layered structures, whereas others do not, remain unclear. The present paper deals with the shallow-level, calc-alkaline, Tarçouate Laccolith (Anti-Atlas, Morocco), which consists of a homogeneous peripheral unit nearly free of igneous layering, and a core unit displaying pervasive igneous layering. The aim of this study is to describe the structural features of the laccolith and to discuss the significance of igneous layering with reference to processes involved in the laccolith construction.

2. The Tarçouate Laccolith: general outline

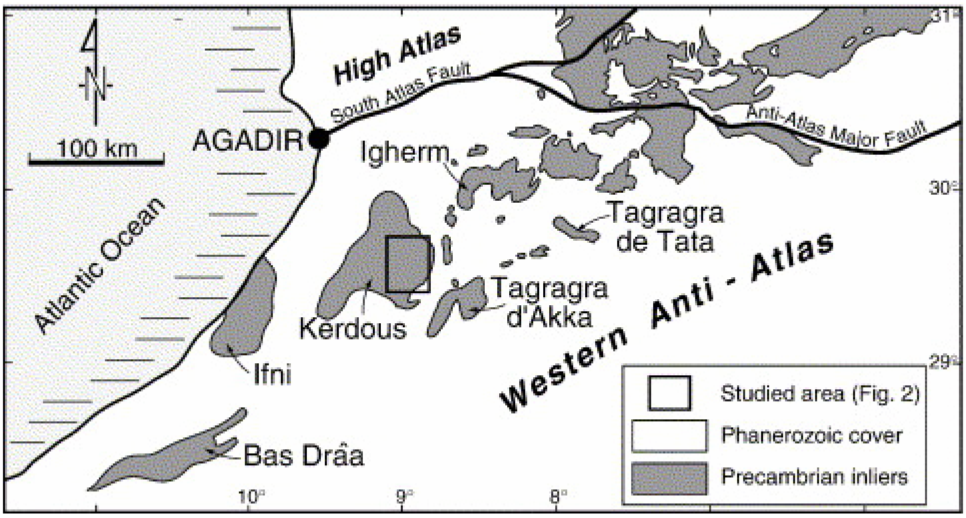

Fig. 1. Simplified geological map of the northern part of the West African craton (from Dallmeyer and Lécorché, 1991) showing the location of the main Palaeoproterozoic inliers of the western Anti-Atlas, and the studied area.

The Tarçouate Laccolith occurs in the Kerdous inlier of the Anti-Atlas Range (Fig. 1). This inlier (Fig. 2) consists of low-grade metaturbidites intruded by plutons of Palaeoproterozoic (e.g., Tahala) and Pan-African ages (e.g., Tarçouate, Tafraoute, Agouni Yessen). Zircon U–Pb data dates the Tarçouate Laccolith at 581 ± 11 Ma (Aït Malek et al., 1998). Further details on its geological setting, petrography and geochemistry may be found in Barbey et al. (2001). Briefly, the Tarçouate Laccolith is 5 km in diameter composite body (Fig. 3) consisting of:

(1) A small outer unit of muscovite granite and pegmatite at the north-eastern edge of the pluton, and as sills in the surrounding schists.

(2) Homogeneous biotite granodiorite surrounding heterogeneous, layered, hornblende granodiorite. Scattered microgranular enclaves of monzodiorite occur throughout the whole pluton. However, enclaves are much more abundant in the core where they occur as swarms (fragmented layers and synplutonic dykes). Dykes of fine-grained biotite granite and aplite are also common in the core. Field relationships and geochemical data (Barbey et al., 2001) suggest that all rock types were emplaced as successive magma pulses before the granodiorites crossed their solidus.

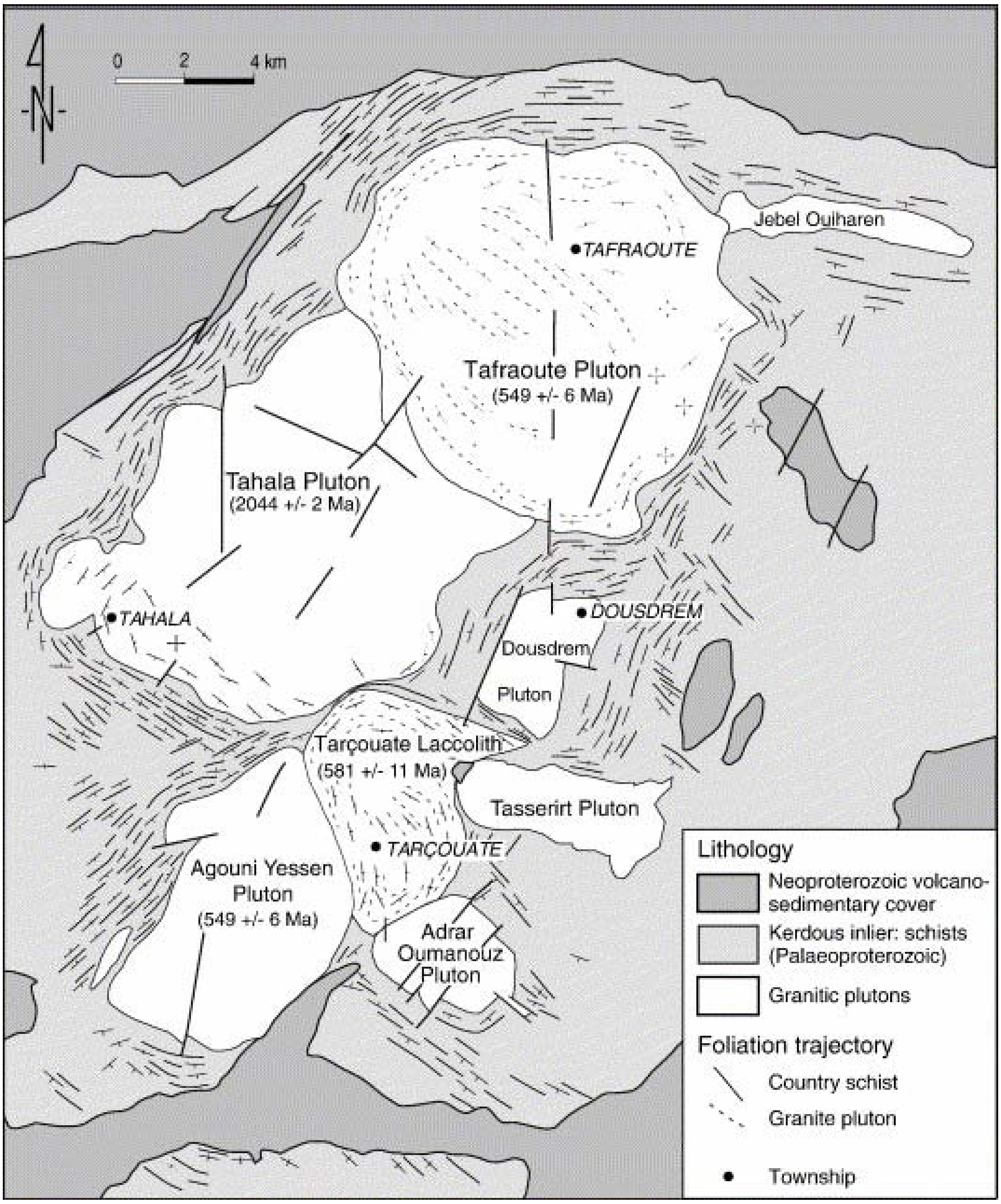

Fig. 2. Geological sketch map of the Tarçouate and Tafraoute areas (redrawn from Choubert, 1963, and author's field work) with zircon U–Pb ages of the Tarçouate (Aït Malek et al., 1998) and Tahala plutons (Barbey et al., 2004), and the Rb–Sr isochron age of the Tafraoute and Agouni Yessen plutons (Charlot, 1982).

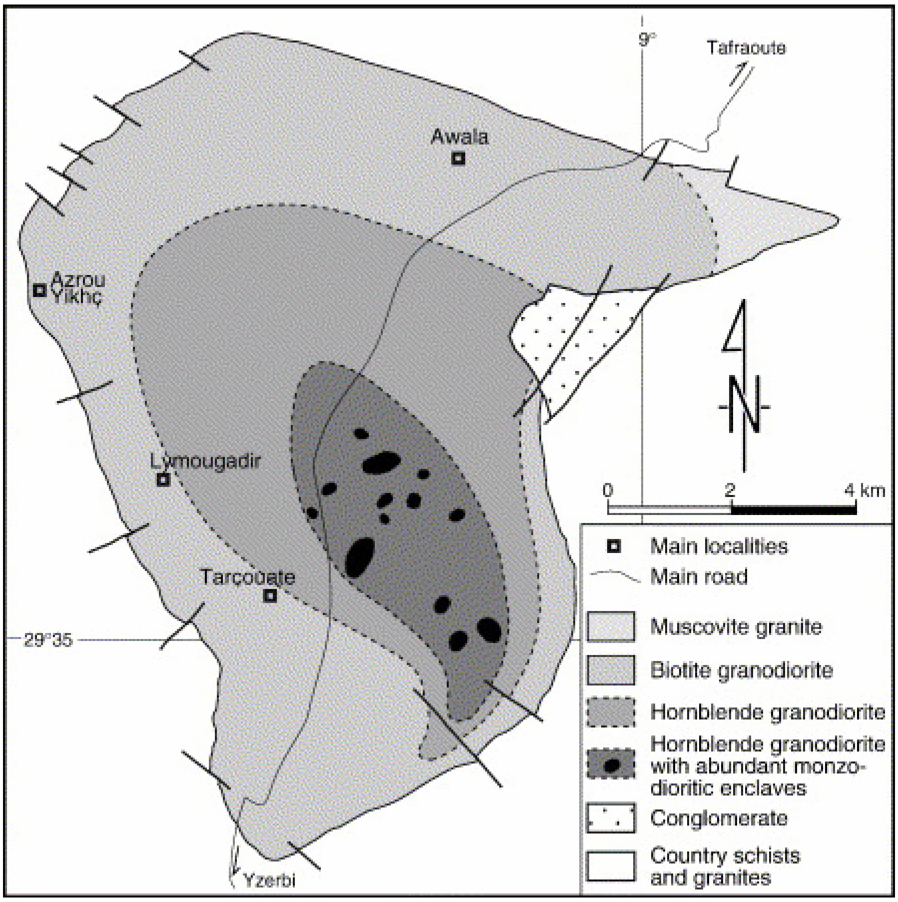

Fig. 3. Geological sketch map of the Tarçouate Laccolith showing the main rock units.

3. Structural data

The Tarçouate Laccolith occurs in a depressed trough bounded by hills of granite and schist (Fig. 4a). Its irregular amoeba-like outline is controlled by older intrusions: the Tahala and Dousdrem plutons to the north, Tasserirt pluton to the east, Adrar Oumanouz pluton to the south, and Agouni Yessen pluton to the west (Fig. 2). To the east, the sills of muscovite granite and pegmatite (Fig. 4b) are locally folded around NS-trending sub-horizontal axes (Fig. 4c) and crosscut by dm-sized normal shear-zones with east-side down movement. To the north, the contact is roughly parallel to the foliation of the country schists, which include tens of metres thick, competent orthogneiss sheets (Fig. 5).

3.1. Foliation and lineation

Foliation within the laccolith is defined by the shape-preferred orientation of biotite, hornblende and feldspars, and is conformable with the orientation of microgranular mafic enclaves. In the core, foliation is weak, commonly dips > 40°, and trends dominantly NW–SE. In the periphery, it is parallel to the country rock foliation and is, in most cases, conformable with the borders of the laccolith. It dips shallower inwards, especially near the north-western boundary along which dips are 20–30° (Fig. 5).

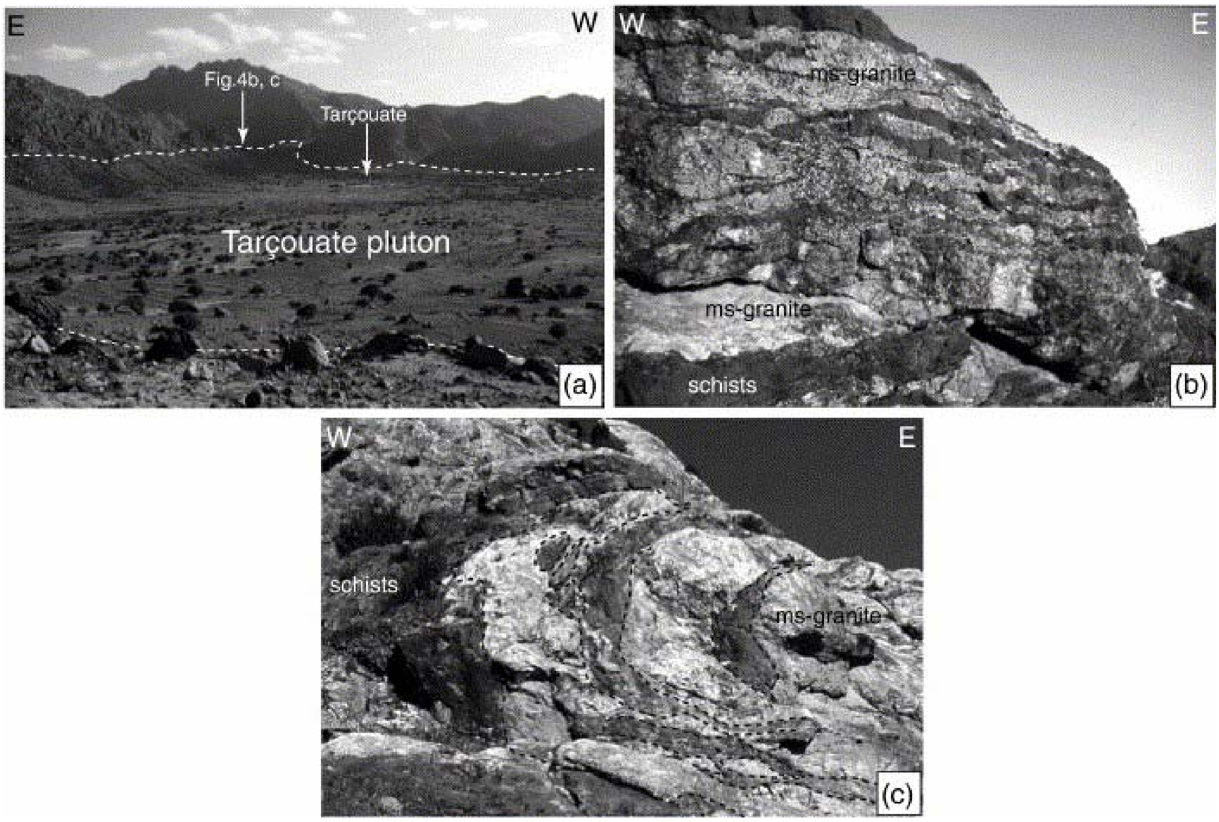

Fig. 4. (a) View of the Tarçouate Laccolith looking south: heights to the east and south correspond to the Kerdous schists and to the Adrar Oumanouz and Agouni Yessen plutons, respectively. (b) and (c) Kerdous schists (dark) at the top of the Tarçouate Laccolith, injected by sills of muscovite granite and pegmatite (light), which are locally folded.

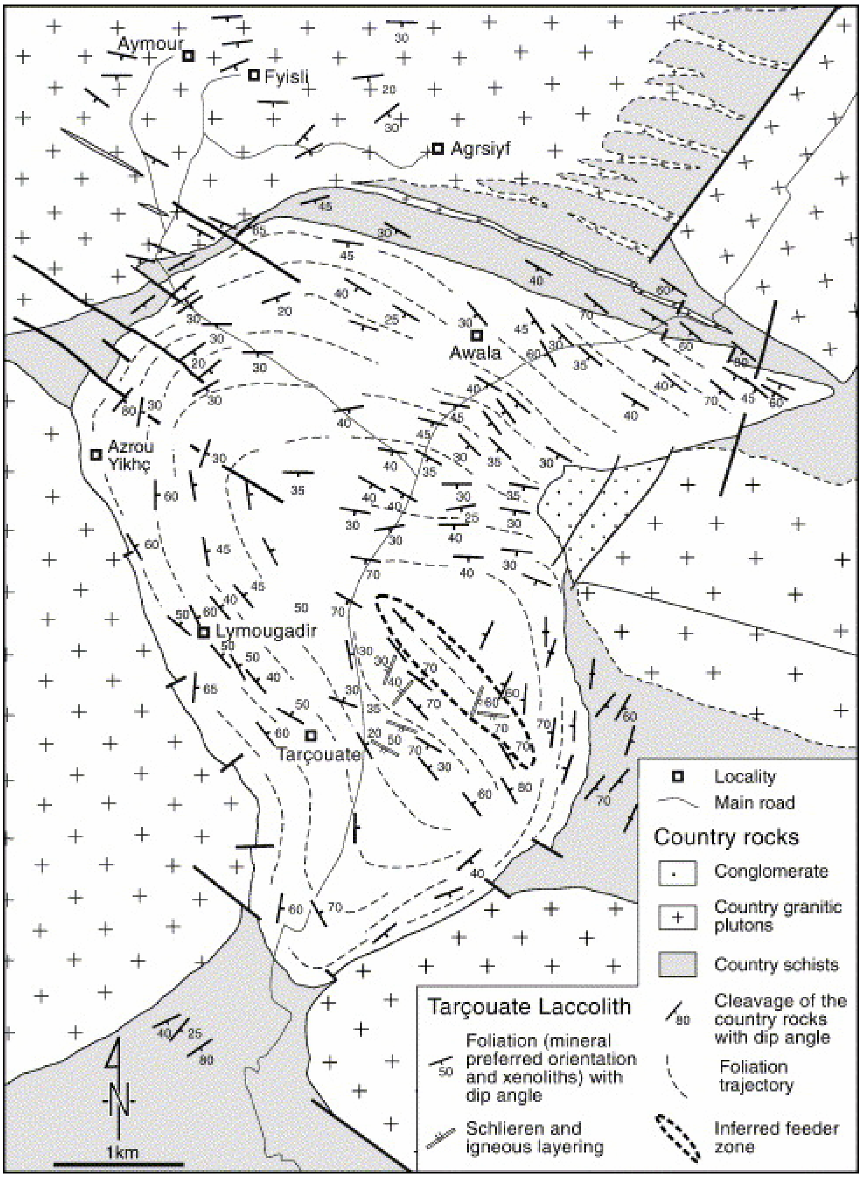

Fig. 5. Map of foliations, schlieren and igneous layering in the Tarçouate Laccolith.

The lineation, defined by the shape-preferred orientation of ferromagnesian minerals and K-feldspar, is parallel to the elongation direction of monzodiorite enclaves. It is sub-horizontal (plunges ≤ 25°) and sub-parallel to the contact in the north-eastern and south-eastern parts (circumferential lineation) where S-fabric is dominant, whereas it plunges steeply inward (> 60°) in the central part of the laccolith (radial lineation) where L-fabric predominates (Fig. 6).

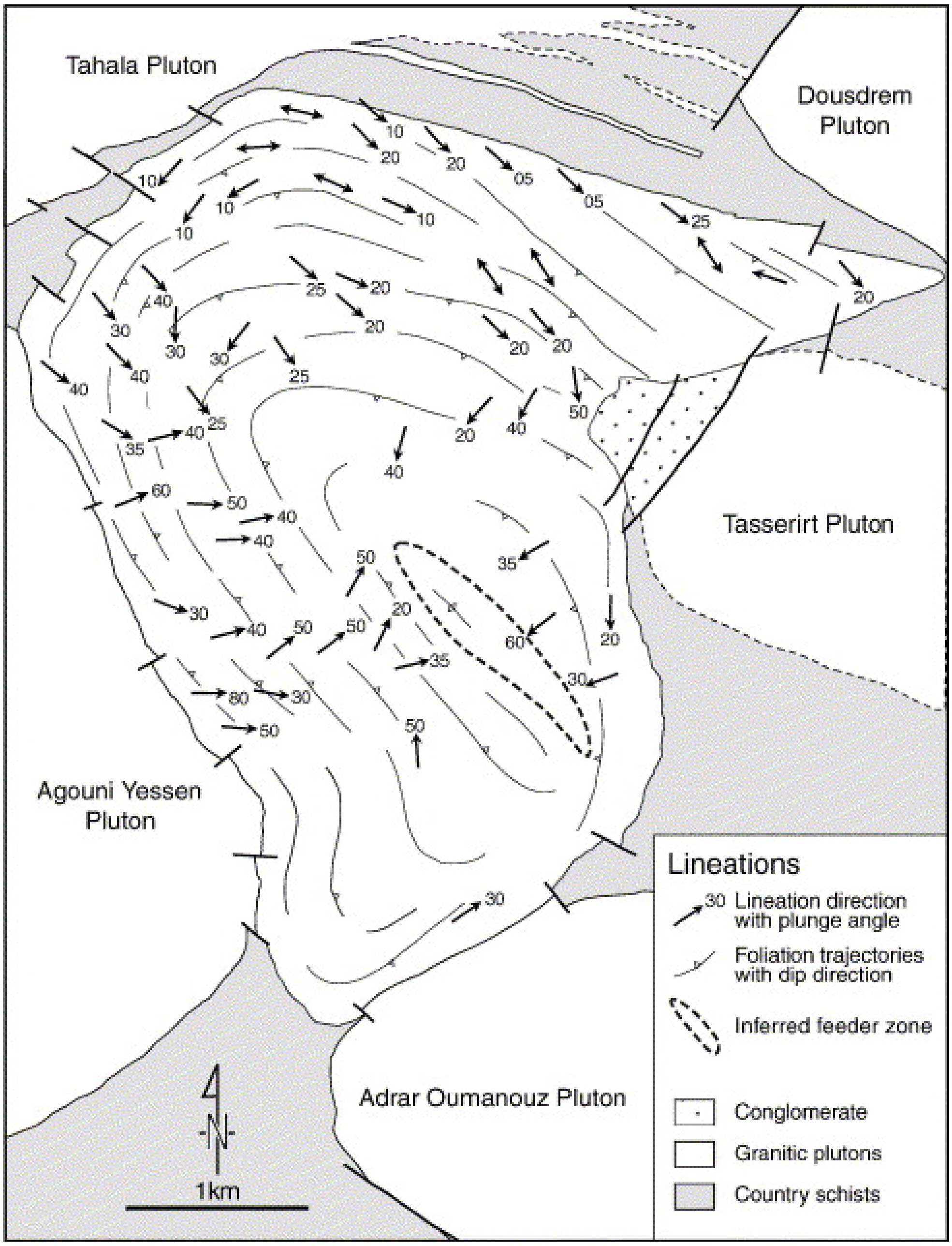

Fig. 6. Map of lineations in the Tarçouate Laccolith.

3.2. Igneous layering

Layering and schlieren are absent from the homogeneous peripheral biotite granodiorite. They are widespread in the core hornblende granodiorite (Fig. 7a) and also occur in dykes of fine-grained biotite granite and aplite cutting through the granodiorite (Fig. 7b).

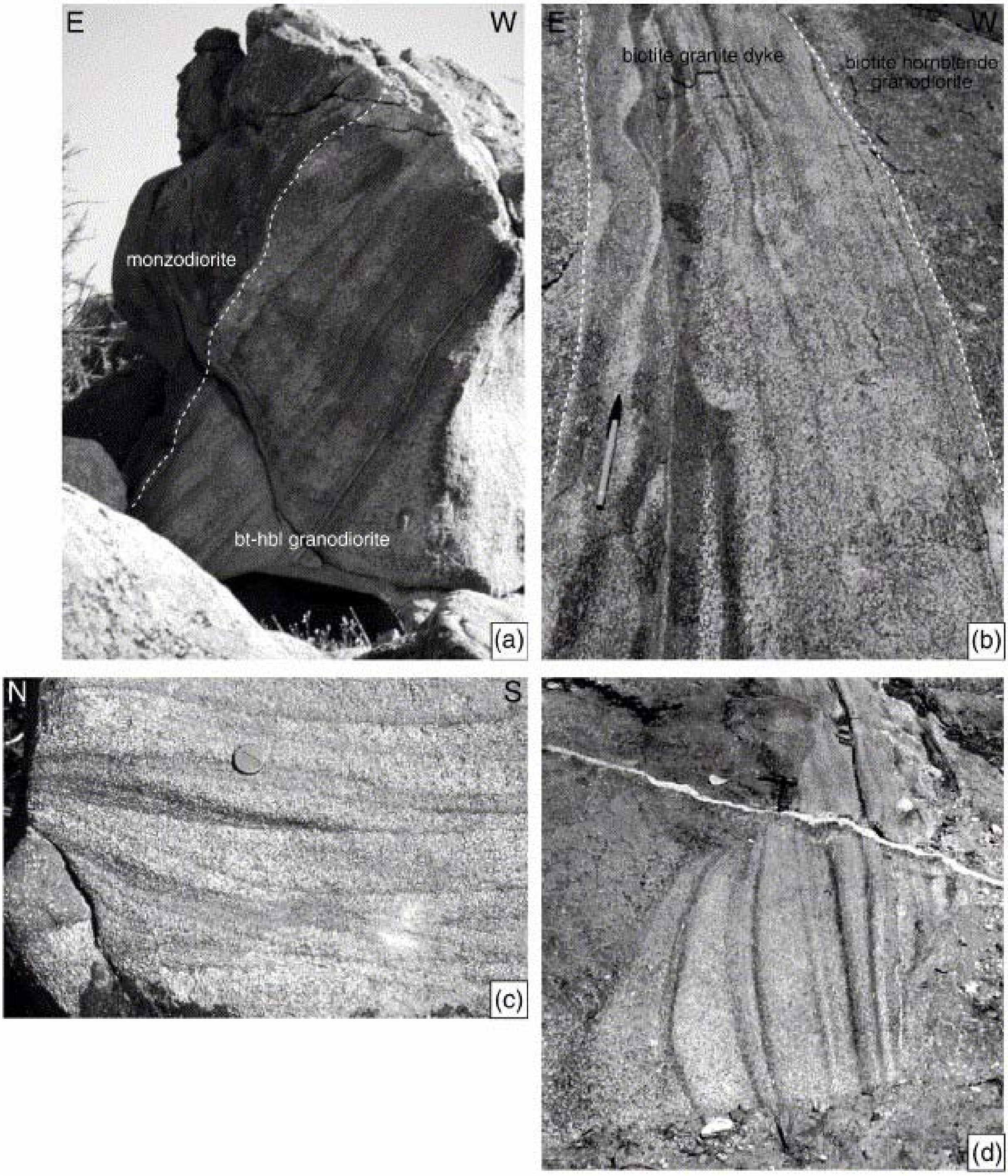

Fig. 7. Igneous layering in the core hornblende granodiorite: (a) banding defined by alternating layers of monzodiorite and granodiorite, and by rhythmic variation of the modal proportions of biotite and hornblende in the granodiorite; (b) sub-vertical modal banding outlined by the proportions of biotite in dykes of biotite granite cutting through granodiorite; note channelling on the right of the pen; (c) cross-stratification in granodiorite; (d) steeply dipping trough banding.

In the hornblende granodiorite, layering is rhythmic, outlined by variation in the proportions of biotite and hornblende (modal layering), with common mineral grading, cross-stratification (Fig. 7c) and trough layering (Fig. 7d). The thin base of each layer is rich in ferromagnesian minerals (30–40 vol.%), consisting of a framework of subhedral to euhedral crystals of biotite and hornblende (0.5–1.5 mm). Biotite is more abundant than hornblende. Hornblende grains may be almost inclusion free, or contain abundant apatite, and occasionally corroded biotite. X_{Mg} values of hornblende (0.43–0.45) and biotite (0.41–0.46) are in a restricted range, with no systematic variations across layering. Al-content of biotite is more variable (2.7–2.95 atom per formula unit). Large euhedral grains of titanite and allanite (1.5–2 mm) are widespread. Plagioclase ($An_{24–36}$) has variable size and shape, locally with resorption features. It occurs as subhedral isometric grains (generally around 1.5 mm, but up to 4 mm) and as laths (4.5 mm in length), usually with oscillatory zoning. It contains small euhedral crystals of hornblende and biotite (0.5 mm). Interstitial phases in the thin base of each layer are quartz and few K-feldspar. There is an upward, gradual though rapid decrease in ferromagnesian mineral content (biotite + hornblende ≤ 15% locally form clusters). Plagioclase remains the dominant phase. Minerals show the same textural features as in the ferromagnesian-rich base, with the exception of K-feldspar, which occurs as both large rounded grains and interstitial poikiloblasts (up to 5 mm across). Secondary phases throughout the layer comprise scarce epidote, chlorite and prehnite.

The magmatic layering is also outlined by quartzofeldspathic segregations (Fig. 8a). Due to outcrop conditions, the layers are visible over some tens of metres only. They are variably oriented but generally dip ≥ 45° and in some cases are sub-vertical. Despite this steepness, we did not observe any slump structures. Rhythmically layered units in the hornblende granodiorite are systematically accompanied with monzodiorite as either metre-thick layers (Fig. 7a) or abundant scattered enclaves (Fig. 8b). The layered units are locally crosscut by sub-vertical, synmagmatic dykes of granodiorite, monzodiorite and aplite. The layering has not been seen to grade into dilacerated enclaves as reported in other plutons (e.g. Gasquet et al., 1995); it wraps around microgranular enclaves, with change in thickness suggesting either flow around rigid objects or compaction-related deformation (Fig. 8c,d).

In dykes of biotite granite and aplite, which are close to vertical, layers are grossly parallel to the dyke walls, but may display crosscutting relationships and contorted structures (Fig. 7b). They are outlined by variations in biotite content and are much more irregular in length and thickness (schlieren-like layers) than layers of the hornblende granodiorite.

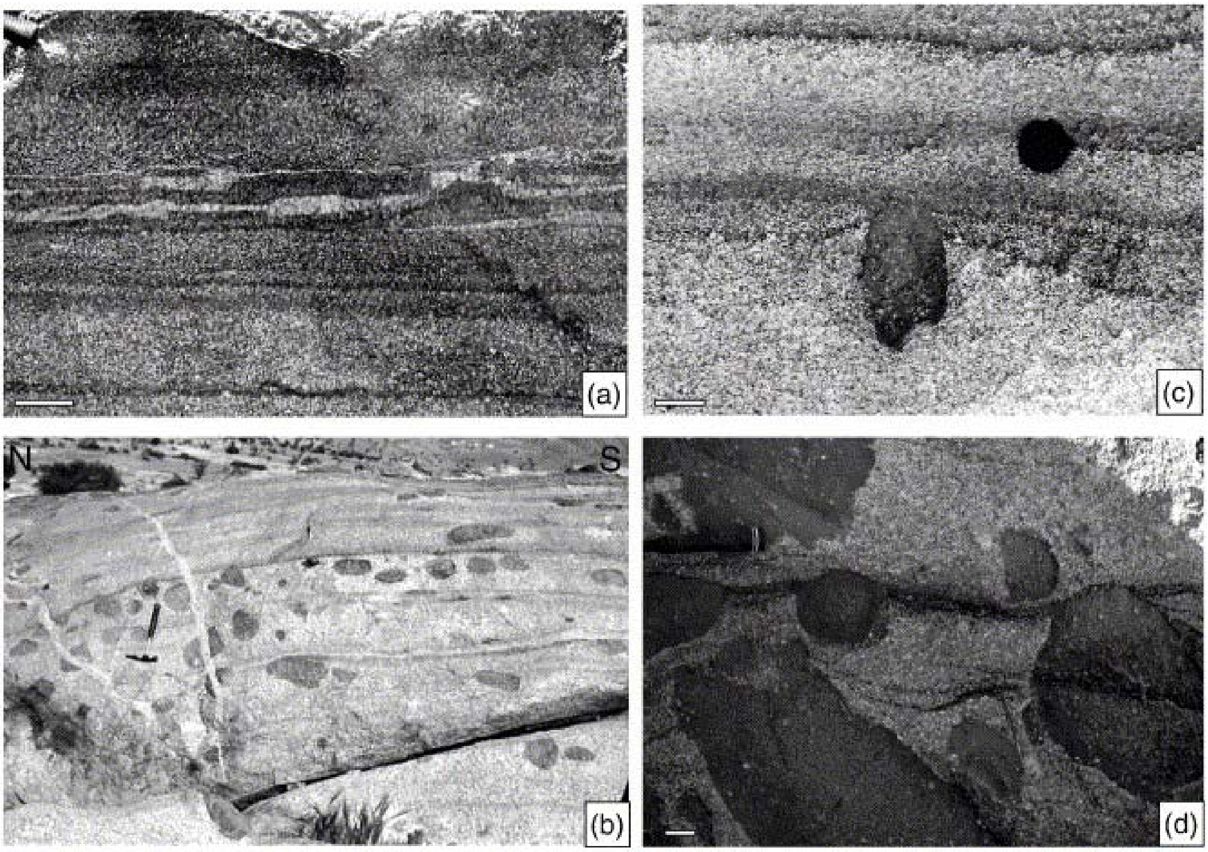

Fig. 8. Igneous layering in the core hornblende granodiorite of the Tarçouate Laccolith: (a) quartzofeldspathic segregations forming cm-thick layers conformable with the modal layering marked by ferromagnesian minerals (scale bar = 8 cm); (b) igneous banding typically accompanied by numerous monzodiorite microgranular enclaves (banding dips 45° away from the viewer); (c) and (d) layering wrapping around and thinned above monzodiorite enclaves (scale bar = 5 cm).

3.3. Distribution of monzodiorite

The proportion of monzodiorite enclaves varies from the periphery towards the core of the laccolith (Fig. 9a). In the peripheral biotite granodiorite, monzodiorite occurs most frequently as centimetre-sized enclaves scattered in the granitic matrix (Fig. 10a). In the core hornblende granodiorite, the monzodiorite enclaves are much more abundant and larger, and show two types of occurrences. One type is local and corresponds to either banded monzodiorite back-veined by granitic material, or proto-dykes (Fig. 10b) crosscutting both the host granodiorite and dykes of biotite granite and aplite. The other type includes decimetre to metre-sized enclaves scattered within the hornblende granodiorite and typically associated with the igneous layering (Fig. 7d). These enclaves have always a sharp, though occasionally lobate contact with the host rock. They commonly contain abundant xenocrysts of ocellar quartz and rounded plagioclase and K-feldspar (Fig. 10c), suggesting a strong mingling with the partially crystallised host granodiorite.

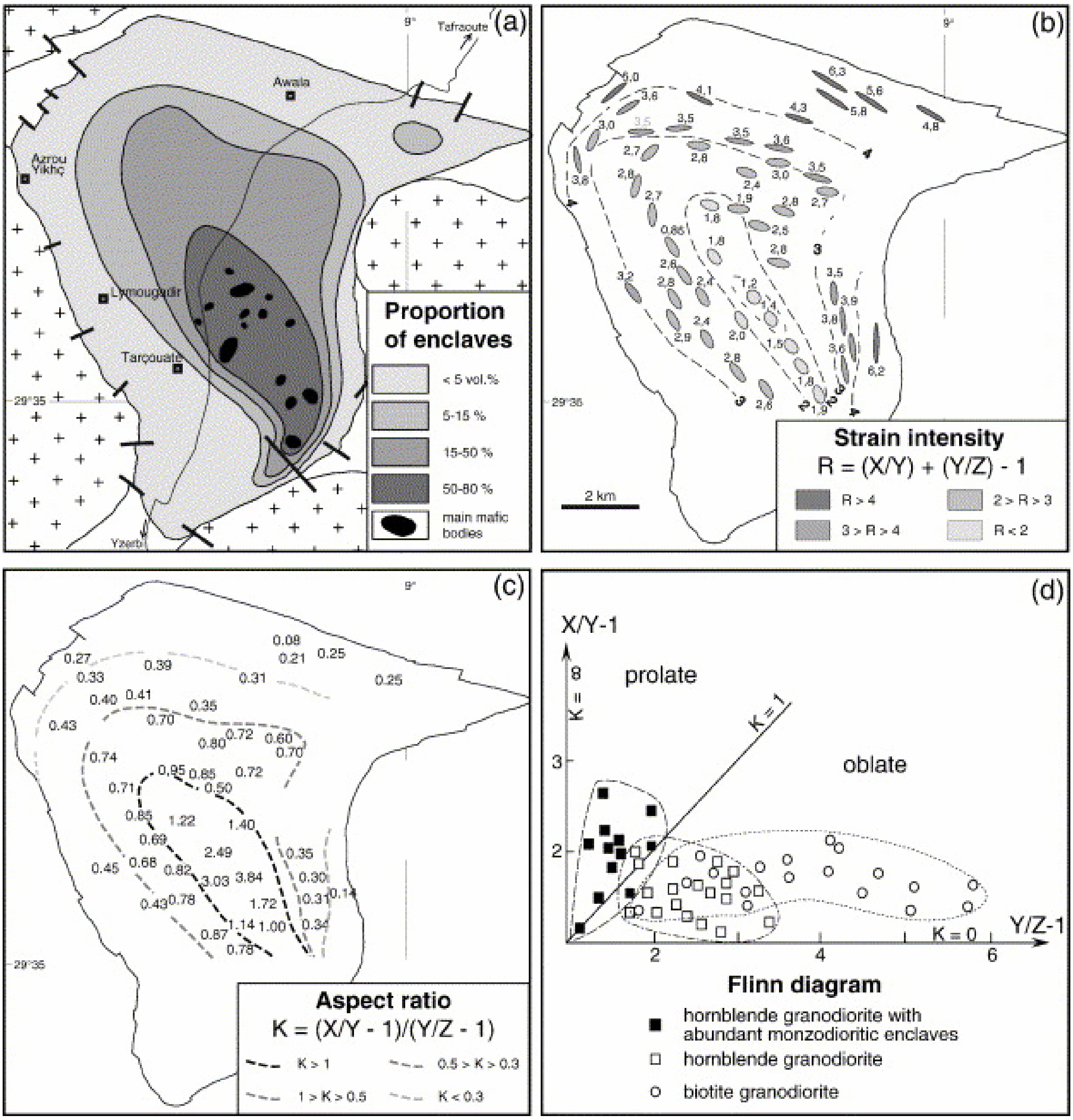

Fig. 9. Monzodioritic microgranular enclaves of the Tarçouate Laccolith: (a) areal distribution; (b) strain intensity $R = (X / Y) + (Y / Z) - 1$ (Watterson, 1968), with $X \geq Y \geq Z$ the three axes of the finite strain ellipsoid; (c) aspect ratio $K = [(X / Y) - 1] / [(Y / Z) - 1]$ of the finite strain ellipsoid (e.g. Ramsay and Huber, 1987); and (d) Flinn diagram (Flinn, 1962).

The enclave shapes and relationships with the host rocks suggest bulk co-axial deformation. No sigmoidal structures were observed, even at the grain-scale; instead, symmetrical pressure shadows occur on ocellar quartz grains in monzodiorite enclaves (Fig. 10d). The enclave shape depends on the position in the pluton, with strain intensity values < 2 in the core and increasing radially towards the periphery (Fig. 9b). Shape-ratios and plots in the Flinn diagram (Fig. 9c,d) indicate that the enclave fabric is slightly prolate in the core hornblende granodiorite and oblate in the peripheral biotite granodiorite, indicating constrictional deformation in the core and flattening at the periphery of the laccolith.

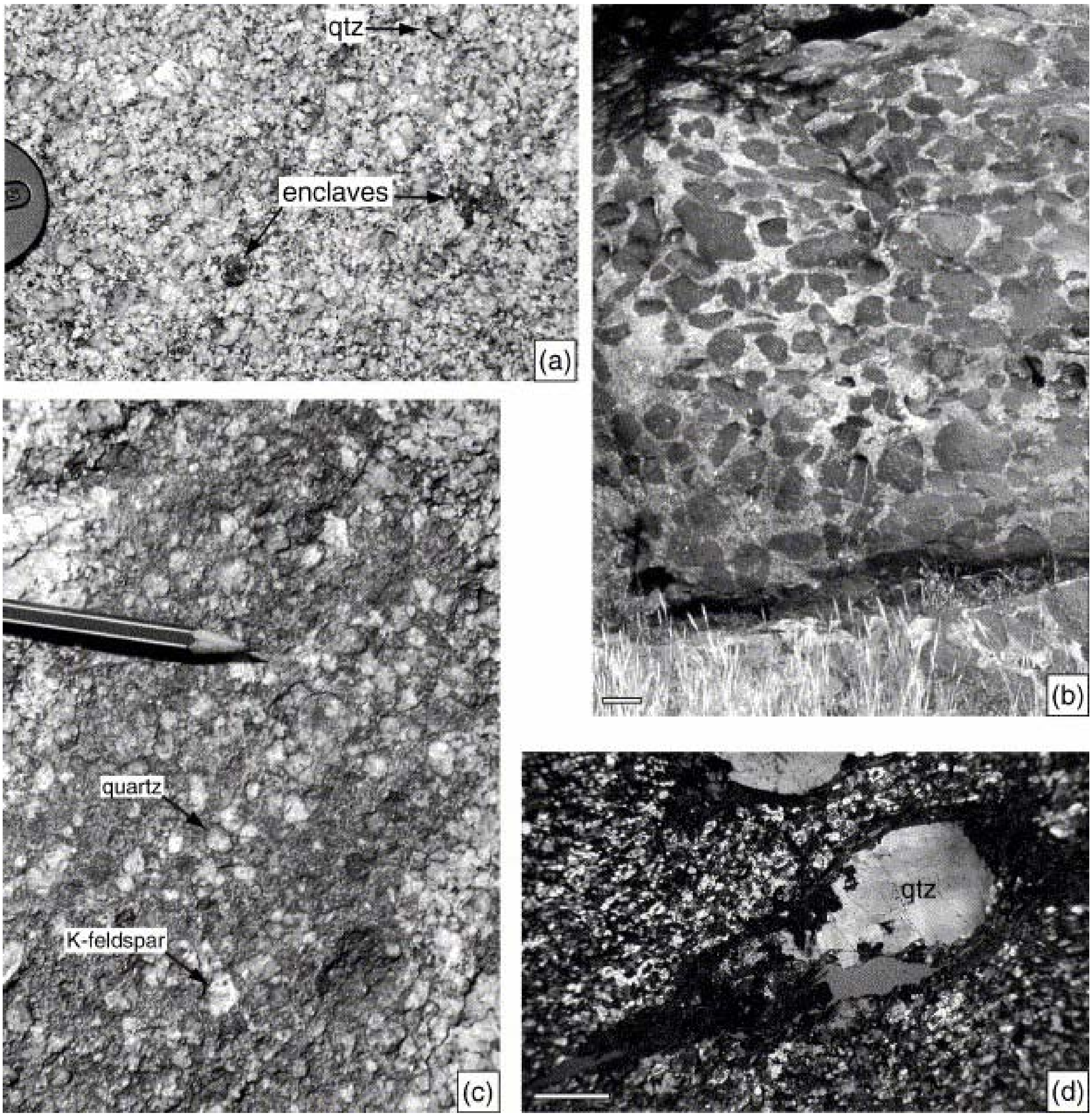

Fig. 10. Monzodiorite microgranular enclaves: (a) cm-sized enclaves in the peripheral biotite granodiorite; (b) enclave swarm corresponding to a proto-dyke in the core hornblende granodiorite (scale bar = 20 cm); (c) close view of (b) showing the large amount of ocellar quartz and rounded feldspar xenocrysts in enclaves; (d) symmetrical pressure fringes around ocellar quartz in hornblende granodiorite (scale bar = 2.5 mm).

4. Discussion

Field, petrographic and geochemical studies indicate that the Tarçouate Laccolith results from the aggregation of three magma batches (Barbey et al., 2001): first muscovite granite, then biotite granodiorite, and finally hornblende granodiorite accompanied by monzodiorite. Synplutonic dykes of fine-grained biotite granite, aplite and monzodiorite crosscut these three magma types. These observations are consistent with the model of pluton construction by aggregation of magma pulses delivered by dykes (e.g. Vigneresse and Clemens, 2000). The presence in the core of many microgranular enclaves and of layers of monzodiorite back-veined and disrupted by granite, along with evidence of depositional features suggest that the Tarçouate Laccolith is similar to the MASLI system described by Wiebe (1993a). Igneous banding in dykes of biotite granite and aplite likely reflects hydrodynamic sorting and will not be dealt with further. We now discuss layering of the hornblende granodiorite. Three basic observations are considered: (i) layering is systematically associated with monzodiorite microgranular enclaves; (ii) it is restricted to the hornblende granodiorite in the core of the laccolith, whereas it is lacking in the peripheral biotite granodiorite; and (iii) it is commonly steeply dipping.

4.1. Evidence for hydrodynamically active system

Two main processes, which are mutually not exclusive, are currently invoked to account for igneous layering (e.g. Tait and Jaupart, 1996): either growth in a thermal boundary layer (crystallization front), or hydrodynamic sorting and crystals settling. In the Tarçouate Laccolith, (i) depositional features such as cross-bedding and trough structures, (ii) lack of cryptic variations in the composition of ferromagnesians minerals across layering and heterogeneity in size and distribution (especially clusters of ferromagnesian minerals) and (iii) the nature of mineral inclusions indicate that the minerals accumulated from an overlying convecting magma reservoir rather than from the progression of a crystallization front. Moreover, quartzofeldspathic segregations nearly parallel but crosscutting layering (Fig. 8a) suggest that compaction contributed to removal of interstitial melt from the cumulate. These features show that differentiation by crystallization in a hydrodynamically active body likely occurred at the level of emplacement.

Two further important points are the close association of enclaves with igneous layering and the texture of cumulate hornblende. Field relationships suggest that mafic enclaves were deposited on an aggrading floor and may have locally formed “rigid” bulges that affected deposition of the overlying layers (Fig. 8c). Moreover, the presence of cumulate hornblende containing corroded biotite (a texture reported in hybrid rocks; e.g. Asrat et al., 2004) suggests contamination of biotite-bearing granitic magma by mafic injection. Accordingly, crystal deposition in each layered sequence was preceded by episodic injection of mafic magma leading to mingling and hybridization. We conclude that deposition of the layered sequences, hence convective stirring, was coeval with mafic replenishments. These close relationships, formerly reported by Wiebe et al. (2002) in the Pyramid Peak pluton, are discussed in the next section.

4.2. Why is igneous layering restricted to the hornblende granodiorite?

Layering may be due to the physicochemical properties of magmas and their ability to convect. We have estimated the viscosity of the melts parent to hornblende and biotite granodiorites using the method of Shaw (1972) with the following two assumptions:

(i) whole-rock analyses of homogeneous hornblende granodiorite (cumulate compositions are avoided) and biotite granodiorite (Table 2, in Barbey et al., 2001) are representative of melt compositions;

(ii) magma water content is estimated at ~2 wt.% and magma temperatures at 850–900 °C for hornblende granodiorite and at ~4.5 wt.% and 750–800 °C for biotite granodiorite from thermometric estimates (Barbey et al., 2001) and solubility data of water in granitic melt (Johannes and Holtz, 1996).

The estimated melt viscosity ($\log\eta$ = 4.8–5.3 and 3.8–4.2 Pa s for the biotite and hornblende granodiorites, respectively) agree with experimental data (Scaillet et al., 1998) and with theoretical calculations (Clemens and Petford, 1999). As a first approximation, if the pluton emplaced by rapid dyke feeding (Brandon et al., 1996 and Johnson et al., 2001) in two stages (biotite granodiorite before hornblende granodiorite), we can use the corresponding Rayleigh numbers. Assuming slowly cooled chambers with a minimum heat flux of 0.4 Wm^{-2} and using the equations and parameters given in Martin et al. (1987), we obtain $Ra > 10^6$ for chamber thickness ≥ 100 m. Therefore, owing to the much larger size of both magmatic units of the Tarçouate Laccolith, the viscosity alone cannot account for the distinct behaviour of the biotite granodiorite (first batch) and the hornblende granodiorite (second batch).

The close association of layering with enclaves raises the question on the relationships between recurrent injection of mafic magma and the development of igneous layering. Huppert and Sparks (1980) discussed the influx dynamics of hot dense ultramafic magma beneath a fractionated lighter basaltic magma, and provided a model for the development of rhythmic layering in mafic intrusions. On the other hand, Wiebe and Collins (1998) and Wiebe et al. (2002) discussed the role of thermal exchange above the mafic replenishments in triggering convection in overlying silicic magma and keeping the magma chamber of MASLI systems active. Weinberg et al. (2001) report channel structures delineated by mafic schlieren in the Tavares Pluton, which they attribute to melt escape and flow sorting related to convection locally driven by heat released from dioritic intrusions. It can be further considered that the thermal input related to recurrent emplacement of mafic magma into the crystallizing chamber likely induces protracted magma crystallization in addition to local convective stirring, hybridization, crystal settling and hydrodynamic sorting, allowing the development of igneous banding.

In the Tarçouate Laccolith, the striking difference in content of mafic enclaves between the peripheral biotite granodiorite and the central hornblende granodiorite likely reflects distinct amounts of mafic replenishment. The close relationship between mafic replenishment and layering is not specific to the Tarçouate Laccolith, but is a systematic feature of calc-alkaline bodies. Famous examples are the Mount Givens Pluton (Reid and Hamilton, 1987 and Tobisch et al., 1997) and the Pyramid Peak Granite (Wiebe et al., 2002), but there are many others (e.g. Kameruka Pluton, Collins et al., 2000; Guernsey Plutonic Complex, Brémond d'Ars, 1990; Pleasant Bay Intrusion, Wiebe, 1993a and Wiebe, 1993b). This suggests that the close association of layering with mafic magmas in plutons is not fortuitous; instead, it shows a connection between convection leading to layering and mafic replenishment triggering thermal perturbation.

4.3. Why is igneous layering steeply dipping?

Another aspect of the problem concerns the attitude of the igneous layering, which dips 45° to 70°. Even though layering may develop with a steep attitude during the progression of a crystallization front against the intrusion wall (e.g. Pons et al., 1995 and Tait and Jaupart, 1996), several lines of evidence suggest that layering is not in its initial position. The absence of slump structures in high angle (up to 70°) cross-stratifications (Fig. 7c) and presence of steep trough layering (Fig. 8a) suggest that these layered structures deposited on shallow-dip surfaces. Supportively, closely symmetrical disposition of igneous layering around mafic enclaves (Fig. 8c), suggests deposition over a rigid object protruding from a near-horizontal surface. One may also argue that there is no reason why the monzodiorite should intrude conformably to the steep layering, a near systematic structural relationship in the Tarçouate Laccolith (Fig. 7a). One expects emplacement as either sub-vertical dykes (as occasionally observed) or sub-horizontal sills as described for example by Wiebe and Collins (1998). These observations indicate that igneous layering in the Tarçouate Laccolith has been tilted. The fact that layering is crosscut by sub-vertical and synplutonic dykes of biotite granite (Fig. 7b), aplite and monzodiorite (Fig. 10b) further indicates that tilting occurred during pluton growth. We attribute the high-angle attitudes to floor sinking in the core of the pluton, possibly in the vicinity of the feeder zone. Downward sinking of the floor of granitic plutons is a counterpart of upward movement of pluton roof in response to magma replenishment (Glazner and Miller, 1997, Cruden, 1998 and Wiebe and Collins, 1998).

4.4. Geometry of the laccolith and emplacement succession

Foliation trajectories are concentric and sub-parallel to both the internal lithological boundaries and the contact with the host rocks. The irregular outline of the Tarçouate Laccolith is closely related to the shape of the neighbouring granitic bodies (Fig. 5) and suggests that emplacement was impeded by these older intrusions. This, along with the low foliation dips in the north-western part, suggests a laccolith shape, an off-centre feeder zone, and a main extension direction towards the area occupied by schists and free of older intrusions, in the NW (Fig. 5). In the core, foliation and lineation both overprint the igneous layering, which suggests that they represent late-strain increments while magma cooled below the rigid percolation threshold (Vigneresse et al., 1996, Paterson et al., 1998 and Barros et al., 2001).

Close to the border of the laccolith (especially in the north and the southeast; Fig. 6), the lineation is mostly circumferential and near-horizontal suggesting stretching parallel to the pluton boundaries along with inflation-related flattening. In the north and northwest, the NW–SE lineation with low plunges towards the core, suggests that the main stretching direction was towards the NW, in accordance with the overall shape of the Tarçouate Laccolith. In the hornblende granodiorite, the lineation at high angle to the foliation suggests radial extension. Due to the viscosity evolution of mafic and silicic magma upon cooling, mafic enclaves are likely to behave as passive markers while the host magma is in near-solidus condition (Scaillet et al., 2000). Therefore, enclave fabrics record strain below the rigid percolation threshold.

The symmetry of structures in the biotite granodiorite suggests that deformation results from co-axial flattening rather than from magmatic flow. Inflation-related flattening is consistent with the biotite granodiorite being emplaced as a first pulse subsequently pressed by injection of the hornblende granodiorite, as first documented in the Chindamora Batholith (Ramsay, 1989). Moreover, it is worth noting that the gradual increase in flattening strain of enclaves towards the periphery of the laccolith is variable: strong where the external contact is close to the feeder zone (eastern part of the pluton, Fig. 9b), much more progressive where the external contact is far from the feeder zone. Foliation and layering are two distinct planar fabrics, with angular relationships in the core hornblende–granodiorite showing foliation younger than layering. We conclude that layering is basically related to convection before the rigid percolation threshold was reached, whereas the regularity and concentric attitude of the foliation results from inflation-related deformation, once magma was consolidated (Fig. 11).

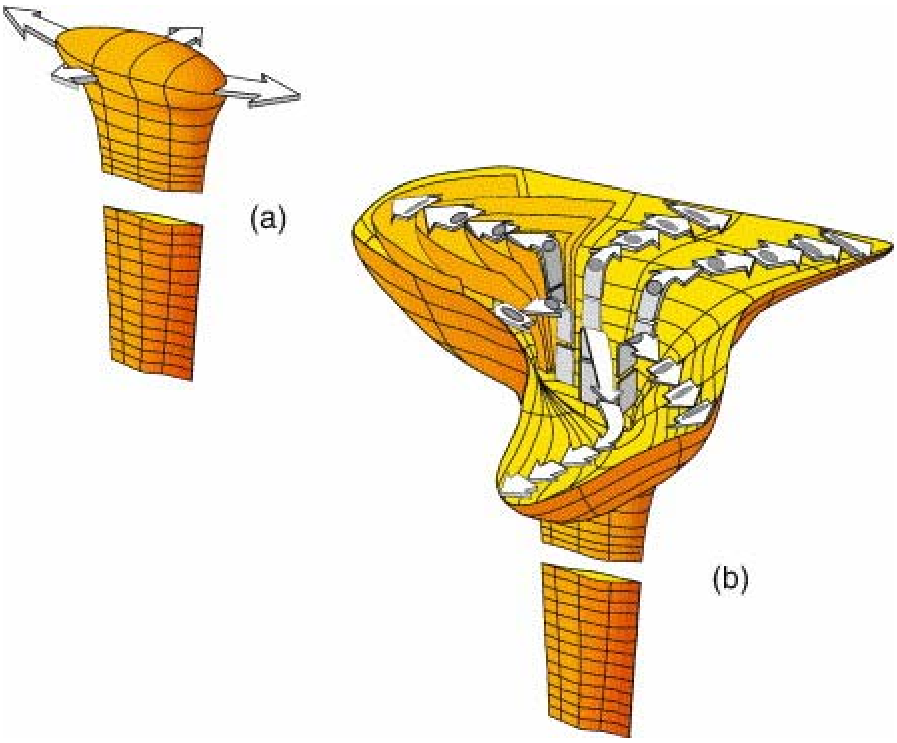

Fig. 11. 3D reconstruction of the emplacement of the Tarçouate Laccolith: (a) initial stage and (b) final stage. Arrows correspond to flow directions of the successive magmatic pulses and carry finite strain ellipses showing the amount of flattening

From the combination of petrological, geochemical and structural data, we infer that four main stages for the growth of the Tarçouate Laccolith can be envisaged.

(1) Following Barbey et al. (2001), the emplacement and differentiation of granodioritic magma similar in composition to the homogeneous hornblende granodiorite occurred in an intermediate deep-seated chamber. This triggered partial melting of country metasedimentary rocks and production of peraluminous leucogranitic magma, and differentiation by fractional crystallization of the parent melt to the biotite granodiorite.

(2) Intrusion of muscovite leucogranite as a small body and as sills in the country schists was followed by emplacement of the main batch of biotite granodiorite. It is not clear whether the monzodioritic enclaves formed by stirring in the deep-seated chamber, or turbulent flow during ascent.

(3) Injection of several pulses of hornblende granodiorite pushed aside the unconsolidated biotite granodiorite and induced both flattening of enclaves and circumferential lineations. Recurrent outpouring of monzodioritic magma accounts for microgranular enclaves and sheets, which spread along the contact between liquid magma and an effectively solidified lower part of the magma chamber. Heat released by the mafic magma pulses maintained local convective stirring and the deposition of minerals and enclaves by density currents (igneous layering).

(4) Renewed magma infilling led to the lateral, upward and downward expansion of the laccolith, folding of the early leucogranite sills in the schists above it by roof lifting (e.g. Pollard and Johnson, 1973 and Acocella, 2000) and tilting of the igneous layers by down-

sagging of the floor. Tilted layering was crosscut by dykes of homogeneous hornblende granodiorite, biotite granite and monzodiorite, showing that the growth of the laccolith continued with the progressive development of a foliation once magma cooled down to its solidus.

5. Conclusions

(1) The Tarçouate Laccolith (Anti-Atlas, Morocco) is a shallow level composite intrusion, which results from the assembly of two main units with contrasting structural features: a homogeneous peripheral biotite granodiorite free of igneous layering, and a pervasively layered internal hornblende granodiorite.

(2) Layering is rhythmic with mineral grading, cross-stratification and trough layering. It commonly dips steeply, owing to post-depositional tilt. Yet, crosscutting synplutonic dykes indicate that tilting occurred during laccolith growth.

(3) Foliation and lineation overprinting igneous layering represent late strain increments. Flattening with circumferential lineations in the peripheral biotite–granodiorite, and constriction with radial lineations in the central hornblende–granodiorite are consistent with the early emplacement of the biotite–granodiorite, subsequently flattened by intrusion of hornblende granodiorite.

(4) The systematic association of layering with monzodiorite, occurring as either metre-thick sheets or scattered enclaves is a systematic feature of calc-alkaline plutons. The recurrent influx of hot mafic magma beneath a fractionated and lighter silicic one and the related thermal input may induce convection and prolonged magma crystallization, which account for the development of igneous layering.

(5) Plutonic bodies are the locus of magma convection and differentiation in relation with replenishment by mafic pulses during crystallization of silicic magma. Convection and the development of igneous banding apparently depend on the recurrence rate of replenishment by mafic pulses. Therefore, as discussed by Spera and Bohrson (2001), the behaviour of a magma chamber is not solely linked to the intrinsic physicochemical properties of magma, but also depends on rates of extrinsic processes like recharge, fractional crystallization and heat loss. This, therefore, suggests that considering the mere assembly of magma pulses is insufficient to understand petrological and structural patterns of magmatic bodies.

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References

Acocella, 2000 V. Acocella, Space accommodation by roof lifting during pluton emplacement at Amiata (Italy), *Terra Nova* **12** (2000), pp. 149–155.

Aït Malek et al., 1998 H. Aït Malek, D. Gasquet, J.M. Bertrand and J. Leterrier, Géochronologie U–Pb sur zircon de granitoïdes éburnéens et panafricains dans les boutonnières protérozoïques d'Igherm, du Kerdous et du Bas Drâa (Anti-Atlas occidental, Maroc), *C. R. Acad. Sci., Paris Sér.2* **327** (1998), pp. 819–826.

Asrat et al., 2003 A. Asrat, G. Gleizes, P. Barbey and D. Ayalew, Magma emplacement and mafic-felsic magma hybridisation: structural evidence from the Pan-African Negash pluton, Northern Ethiopia, *J. Struct. Geol.* **25** (2003), pp. 1451–1469.

Asrat et al., 2004 A. Asrat, P. Barbey, J.N. Ludden, L. Reisberg, G. Gleizes and D. Ayalew, Petrology and isotope geochemistry of the Pan-African Negash pluton, Northern Ethiopia: mafic-felsic magma interactions during the construction of shallow-level calc-alkaline plutons, *J. Petrol.* **43** (2004), pp. 1147–1179.

Barbey et al., 2001 P. Barbey, H. Nachit and J. Pons, Magma–host interactions during differentiation and emplacement of a shallow-level, zoned granitic pluton (Tarçouate pluton, Morocco): implications for magma emplacement, *Lithos* **58** (2001), pp. 125–143.

Barbey et al., 2004 P. Barbey, F. Oberli, J.P. Burg, H. Nachit, J. Pons and M. Meier, The Palaeoproterozoic in western Anti-Atlas (Morocco): a clarification, *J. Afr. Earth Sci. Spec., Issue Key Points on African Geology* **vol. 39** (2004), pp. 239–246.

Barrière, 1981 M. Barrière, On curved laminae, graded layers, convection currents and dynamic crystal sorting in the Ploumanac'h (Brittany) subalkaline granite, *Contrib. Mineral. Petrol.* **77** (1981), pp. 214–224.

Barros et al., 2001 C.E.M. Barros, P. Barbey and A.M. Boullier, The role of magma pressure, tectonic stress and crystallization progress in the emplacement of syntectonic granites. The A-type Estrela Granite Complex (Carajas Mineral Province, Brazil), *Tectonophysics* **343** (2001), pp. 93–109.

Blenkinsop and Treloar, 2001 T.G. Blenkinsop and P.J. Treloar, Tabular intrusion and folding of the late Archaean Murehva granite, Zimbabwe, during regional shortening, *J. Geol. Soc. (Lond.)* **158** (2001), pp. 653–664.

Brandon et al., 1996 A.D. Brandon, R.A. Creaser and T. Chacko, Constraints on rates of granitic magma transport from epidote dissolution kinetics, *Science* **271** (1996), pp. 1845–1848.

Brémond d'Ars, 1990 J. Brémond d'Ars, Estimation de propriétés rhéologiques des magmas par l'étude des instabilités gravitaires. Pétrologie du complexe plutonique lité de Guernesey, *Mém. Doc. Centre Arm. Etud. Struct. Socles, Rennes* **vol. 35** (1990) 370 pp..

Brémond d'Ars and Davy, 1991 J. Brémond d'Ars and P. Davy, Gravity instabilities in magma chambers: rheological modelling, *Earth Planet. Sci. Lett.* **105** (1991), pp. 319–329.

Cawthorn, 1996 R.G. Cawthorn, Layered Intrusions, Elsevier, Amsterdam (1996) 531 pp..

Charlot, 1982 R. Charlot, Caractérisation des événements éburnéens et panafricains dans l'Anti-Atlas marocain. Apport de la méthode géochronologique Rb/Sr, *Notes Mém. Serv. Géol. Maroc* **313** (1982) (106 pp.).

Choubert, 1963 G. Choubert, Histoire géologique du Précambrien de l'Anti-Atlas, *Notes Mém. Serv. Geol. (Morocco)* **162** (1963) (352 pp.).

Clarke and Clarke, 1998 D.B. Clarke and G.K.C. Clarke, Layered granodiorites at Chebucto Head, South Mountain batholith, Nova Scotia, *J. Struct. Geol.* **20** (1998), pp. 1305–1324.

Clemens and Mawer, 1992 J.D. Clemens and C.K. Mawer, Granitic magma transport by fracture propagation, *Tectonophysics* **204** (1992), pp. 339–360.

Clemens and Petford, 1999 J.D. Clemens and N. Petford, Granitic melt viscosity and silicic magma dynamics in contrasting tectonic setting, *J. Geol. Soc. (Lond.)* **156** (1999), pp. 1057–1060

Collins and Sawyer, 1996 W.J. Collins and E.W. Sawyer, Pervasive granitoid magma transfer through the lower-middle crust during non co-axial compressional deformation, *J. Metamorph. Geol.* **14** (1996), pp. 565–579.

Collins et al., 2000 W.J. Collins, S.W. Richards, B. Healy and R.A. Wiebe, Granite magma transfer, pluton construction, the role of coeval mafic magmas, and the metamorphic response: southeastern Lachland Fold Belt Field Guide, *Geol. Soc. Aust., FP* **3** (2000) (142 pp.).

Corriveau and Leblanc, 1995 L. Corriveau and D. Leblanc, Sequential nesting of magmas in marble, southwestern Grenville Province, Québec: from fracture propagation to diapirism, *Tectonophysics* **246** (1995), pp. 183–200.

Cruden, 1998 A.R. Cruden, On the emplacement of tabular granites, *J. Geol. Soc. (Lond.)* **155** (1998), pp. 852–862.

Dallmeyer and Lécorché, 1991 R.D. Dallmeyer and J.P. Lécorché, Introduction. In: R.D. Dallmeyer and J.P. Lécorché, Editors, *The West-African Orogens and Circum-Atlantic Correlatives*, Springer-Verlag, Berlin (1991), pp. 3–5.

Deniel et al., 1987 C. Deniel, P. Vidal, A. Fernandez, P. Le Fort and J.J. Peucat, Isotopic study of the Manaslu granite (Himalaya, Nepal): inferences on the age and source of Himalayan leucogranites, *Contrib. Mineral. Petrol.* **96** (1987), pp. 78–92.

Fernandez and Gasquet, 1994 A. Fernandez and D. Gasquet, Relative rheological evolution of chemically contrasted coeval magmas: example of the Tichka plutonic complex (Morocco), *Contrib. Mineral. Petrol.* **116** (1994), pp. 316–326.

Flinn, 1962 D. Flinn, On folding during three dimensional progressive deformation, *J. Geol. Soc. (Lond.)* **118** (1962), pp. 385–428.

Gasquet et al., 1995 D. Gasquet, A. Fernandez, C. Mahé and A.M. Boullier, Origine des rubanements dans les granitoïdes : exemple du monzogranite de Brignogan-Plouescat (NW du Massif armoricain), *C. R. Acad. Sci., Sér. 2 Paris* **321** (1995), pp. 369–376.

Glazner and Miller, 1997 A.F. Glazner and D.M. Miller, Late-stage sinking of plutons, *Geology* **25** (1997), pp. 1099–1102.

Hallot et al., 1996 E. Hallot, P. Davy, J. Brémond d'Ars, B. Auvray, H. Martin and H. Van Damme, Non-Newtonian effects during injection in partially crystallized magmas, *J. Volcanol. Geotherm. Res.* **71** (1996), pp. 31–44.

Hodson, 1998 M.E. Hodson, The origin of igneous layering in the Nunarsuit syenite, South Greenland, *Mineral. Mag.* **62** (1998), pp. 9–27.

Huppert and Sparks, 1980 H.E. Huppert and R.S. Sparks, The fluid dynamics of a basaltic magma chamber replenished by influx of hot, dense ultrabasic magma, *Contrib. Mineral. Petrol.* **75** (1980), pp. 279–289.

Irvine, 1982 T.N. Irvine, Terminology for layered intrusions, *J. Petrol.* **23** (1982), pp. 127–162.

Johannes and Holtz, 1996 W. Johannes and F. Holtz, Petrogenesis and Experimental Petrology of Granitic Rocks, Springer-Verlag, Berlin, Heidelberg (1996) 335 pp..

Johnson et al., 2001 S.E. Johnson, M. Alberz and S.R. Paterson, Growth rates of dike-fed plutons: are they compatible with observation in the middle and upper crust?, *Geology* **29** (2001), pp. 727–730.

Komar, 1972 P.D. Komar, Flow differentiation in igneous dykes and sills: profiles of velocity and phenocryst concentration, *Geol. Soc. Am. Bull.* **83** (1972), pp. 3443–3448.

Komar, 1976 P.D. Komar, Phenocryst interactions and the velocity profile of magma flowing through dikes or sills, *Geol. Soc. Am. Bull.* **87** (1976), pp. 1336–1342.

Martin et al., 1987 D. Martin, R.W. Griffiths and I.H. Campbell, Compositional and thermal convection in magma chambers, *Contrib. Mineral. Petrol.* **96** (1987), pp. 465–475.

McNulty et al., 2000 B.A. McNulty, O.T. Tobisch, A.R. Cruden and S. Gilder, Multistage emplacement of the Mount Givens pluton, central Sierra Nevada batholith, California, *Geol. Soc. Am. Bull.* **112** (2000), pp. 119–135.

Parsons, 1987 I. Parsons, Origins of igneous layering, *NATO ASI Series, Reidel Publ. Cie, Dordrecht* (1987) 666 pp..

Parsons and Becker, 1987 I. Parsons and S. Becker, Layering, compaction and post-magmatic processes in the Klokken intrusion. In: I. Parsons, Editor, *Origins of Igneous Layering. NATO ASI Series, Reidel Publ. Cie, Dordrecht* (1987), pp. 29–92.

Paterson and Vernon, 1995 S.R. Paterson and R.H. Vernon, Bursting the bubble of ballooning plutons: a return to nested diapirs emplaced by multiple processes, *Geol. Soc. Am. Bull.* **107** (1995), pp. 1356–1380.

Paterson et al., 1998 S.R. Paterson, T.K. Powler Jr., K.L. Scmidt, A.S. Yoshinobu, E.S. Yuan and R.B. Miller, Interpreting magmatic fabric patterns in plutons, *Lithos* **44** (1998), pp. 53–82.

Petford, 1996 N. Petford, Dykes or diapirs?, *Trans. R. Soc. Edinb. Earth Sci.* **87** (1996), pp. 105–114.

Petford et al., 2000 N. Petford, A.R. Cruden, M.J.W. McCaffrey and J.L. Vigneresse, Granite magma formation, transport and emplacement in the Earth's crust, *Nature* **408** (2000), pp. 669–673.

Pitcher, 1993 W.S. Pitcher, The Nature and Origin of Granite, Blackie/Chapman & Hall (1993) 321 pp..

Pollard and Johnson, 1973 D.D. Pollard and A.M. Johnson, Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah, II: bending and failure of overburden layers and sill formation, *Tectonophysics* **18** (1973), pp. 311–354.

Pons et al., 1995 J. Pons, P. Barbey, D. Dupuis and J.M. Léger, Mechanism of pluton emplacement and structural evolution of a 2.1 Ga juvenile continental crust. The Birimian of Southwestern Niger, *Precambrian Res.* **70** (1995), pp. 281–301.

Ramsay, 1989 J.G. Ramsay, Emplacement kinematics of a granite diapir: the Chindamora batholith, Zimbabwe, *J. Struct. Geol.* **11** (1989), pp. 191–209.

Ramsay and Huber, 1987 J.G. Ramsay and M.I. Huber, The Techniques of Modern Structural Geology, vol. 2: Folds and Fractures, Academic Press, London (1987).

Reid and Hamilton, 1987 J.B. Reid Jr. and M.A. Hamilton, Origin of Sierra Nevadan granite: evidence from small scale composite dikes, *Contrib. Mineral. Petrol.* **96** (1987), pp. 441–454.

Roberts et al., 2000 M.P. Roberts, C. Pin, J.D. Clemens and J.L. Paquette, Petrogenesis of mafic and felsic plutonic rock associations: the calc-alkaline Quérigut complex, French Pyrenees, *J. Petrol.* **41** (2000), pp. 809–844.

Saint-Blanquat et al., 2001 M. Saint-Blanquat, R.D. de Law, J.L. Bouchez and S.S. Morgan, Internal structure and emplacement of the Papoose Flat pluton: an integrated structural, petrographic, and magnetic susceptibility study, *Geol. Soc. Am. Bull.* **113** (2001), pp. 976–995.

Scaillet et al., 1996 B. Scaillet, H. Behrens, F. Schulze and M. Pichavant, Water contents of felsic melts: application to the rheological properties of granitic magmas, *Trans. R. Soc. Edinb. Earth Sci.* **87** (1996), pp. 57–64.

Scaillet et al., 1997 B. Scaillet, F. Holtz and M. Pichavant, Rheological properties of granitic magmas in their crystallization range. In: J.L. Bouchez, D.H.W. Hutton and W.E. Stephens, Editors, *Granite: From Segregation of Melt to Emplacement Fabrics*, Kluwer Academic Publ. (1997), pp. 11–29.

Scaillet et al., 1998 Scaillet, B., Holtz, F., Pichavant M., 1998. Phase equilibrium constraints on the viscosity of silicic magmas 1. Volcanic-plutonic comparison. J. Geophys. Res., 103 27,257–27,266.

Scaillet et al., 2000 B. Scaillet, A. Whittington, C. Martel, M. Pichavant and F. Holtz, Phase equilibrium constraints on the viscosity of silicic magmas II: implications for mafic-silicic mixing processes, *Trans. R. Soc. Edinb. Earth Sci.* **91** (2000), pp. 61–72.

Seaman et al., 1995 S.J. Seaman, E.E. Scherer and J.J. Standish, Multistage magma mingling and the origin of flow banding in the Aliso lava dome, Tumacacori Mountains, southern Arizona, *J. Geophys. Res.* **100** (1995), pp. 8381–8398.

Shaw, 1972 H.R. Shaw, Viscosities of magmatic silicate liquids: an empirical method of prediction, *Am. J. Sci.* **272** (1972), pp. 870–893.

Spera and Bohrson, 2001 F.J. Spera and W.A. Bohrson, Energy-constrained open-system magmatic processes I: general model and energy-constrained assimilation and fractional crystallisation (EC-AFC) formulation, *J. Petrol.* **42** (2001), pp. 999–1018.

Tait and Jaupart, 1996 S.R. Tait and C. Jaupart, The production of chemically stratified and accumulate plutonic igneous rocks, *Mineral. Mag.* **60** (1996), pp. 99–114.

Tobisch et al., 1997 O.T. Tobisch, B.A. McNulty and R.H. Vernon, Microgranitoid enclave swarms in granitic plutons, central Sierra Nevada, California, *Lithos* **40** (1997), pp. 321–339.

Vigneresse and Clemens, 2000 J.L. Vigneresse and J.D. Clemens, Granitic magma ascent and emplacement: neither diapirism nor neutral buoyancy. In: B. Vendeville, Y. Mart and J.L. Vigneresse, Editors, *Slate, Shale and Igneous Diapirs in and Around Europe*, *Geol. Soc. London, Spec. Publ.* **vol. 174** (2000), pp. 1–19.

Vigneresse et al., 1996 J.L. Vigneresse, P. Barbey and M. Cuney, Rheological transitions during partial melting and crystallisation with application to felsic magma segregation and transfer, *J. Petrol.* **37** (1996), pp. 1579–1600.

Watterson, 1968 J. Watterson, Homogeneous deformation of the gneisses of Vesterland, Southwest Greenland, *Grön. Geol. Unders. Bull.* **175** (1968), pp. 1–78.

Weinberg et al., 2001 R.F. Weinberg, A.N. Sial and R.R. Pessoa, Magma flow within the Tavares pluton, northeastern Brazil: compositional and thermal convection, *Geol. Soc. Am. Bull.* **113** (2001), pp. 508–520.

Wiebe, 1993a R.A. Wiebe, Basaltic injections into floored silicic magma chambers, *EOS, Trans. Am. Geophys. Union* **74** (1993), pp. 1–3.

Wiebe, 1993b R.A. Wiebe, The Pleasant Bay layered gabbro-diorite, Coastal Maine: ponding and crystallization of basaltic injections into a silicic magma chamber, *J. Petrol.* **34** (1993), pp. 461–489.

Wiebe, 1996 R.A. Wiebe, Mafic-silicic layered intrusions: the role of basaltic injections on magmatic processes and the evolution of silicic magma chambers, *Trans. R. Soc. Edinb. Earth Sci.* **87** (1996), pp. 233–242.

Wiebe and Collins, 1998 R.A. Wiebe and W.J. Collins, Depositional features and stratigraphic sections in granitic plutons: implications for the emplacement and crystallization of granitic magmas, *J. Struct. Geol.* **20** (1998), pp. 1273–1289.

Wiebe et al., 2002 R.A. Wiebe, K.D. Blair, D.P. Hawkins and C.P. Sabine, Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California, *Geol. Soc. Am. Bull.* **114** (2002), pp. 909–920.